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Energy in Agriculture: Energy Resource Series for Youth and Adult Energy Programs: 10. Water

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ENERGY IN AGRICULTURE

Energy Resource Series for Youth and Adult Energy Programs

10. Water

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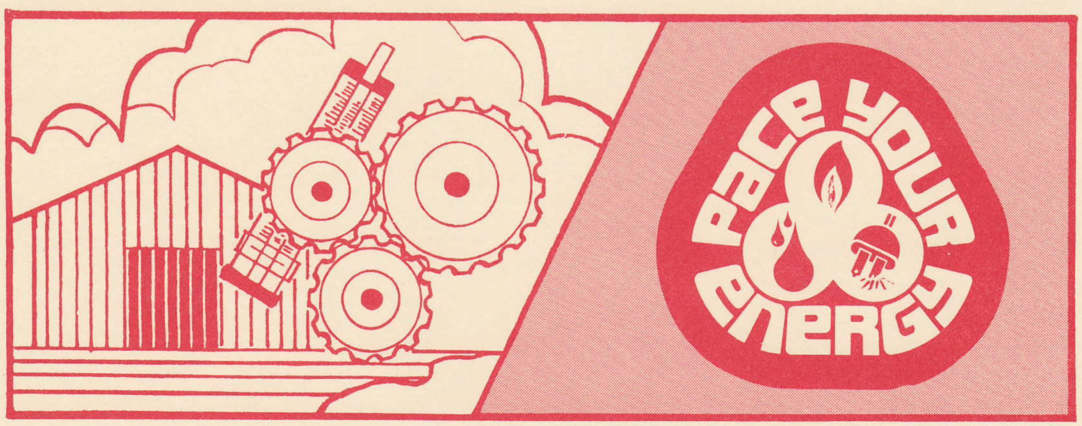

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Preface

There is vast potential energy in water that has fallen on land and is returning to the sea through natural waterways. This is caused by the force of gravity. It is up to man to survey all these possibilities and erect barriers to impede the natural flow of water at strategic locations and impound the water for use as needed.

When producing water power, there is very little pollution. This fact alone makes water power attractive. But, the biggest and most attractive advantage of all is that the source is renewable.

We must realize that such potential energy is not free; there are enormous costs involved in the physical facilities required to harness water. However, if the facilities are located and designed correctly, benefits other than just power may be achieved.

This is the tenth publication in a 12-part energy resource series designed for the adult and student with a serious interest in the energy situation. Each publication examines a different energy source and considers the advantages and disadvantages associated with its use.

When necessary, diagrams and/or tables are used to clarify or elaborate upon information found in the text. Questions with answers are included at the end of each publication so that you can test what you have learned.

The author wishes to thank Robert L. Fehr and Linda A. Bach of the Department of Agricultural Engineering, University of Kentucky, for reviewing the text.

The Energy Resource Series for Youth and Adult Energy Programs includes the following publications:

AEES-21	Energy Overview
AEES-22	Definitions
AEES-23	Oil and Gas
AEES-24	Coal
AEES-25	Solar
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Energy Resource Series for Youth and Adult Energy Programs

10. Water

Natural Advantages of Water Power

Since early history, water has furnished man with energy. Man has always moved and settled along rivers and streams, because water makes travel easier. He soon learned to capture the movement of water in rivers, creeks and streams by inserting a wheel.

Water presents a great source of power. It has been estimated that if every available location for water power were developed, regardless of economic and environmental considerations, there would be between three and four times the power derived from all other sources. But this is impractical, because in many instances it would take more energy in materials and construction than the water would return.

Water power does have several advantages. It is dependable, controllable, relatively safe and renewable. In contrast, fossil fuels or nuclear fuel can be used only once, but water can return again and again to generate power. This is the greatest advantage of water power.

The Natural Water Cycle

Water power is similar to wind power because the power source for each one is the sun. Heat from the sun causes water to evaporate from the earth's surface, that is, become a gas or vapor, and be lifted into the upper regions of the atmosphere by rising currents of air. Upon rising, the water vapor enters cooler air. When it cools sufficiently, it condenses into small droplets. When these droplets become large enough, they can fall through the rising air currents to the earth. These droplets gradually make their way back to the oceans, lakes and rivers to start the cycle over again. This cycle is aided by gravity. The complete water cycle is depicted in Figure 1.

It is after droplets have returned to earth and have been congregated into small channels that man is able to take advantage of this source of energy. In this respect, water is quite different from the wind. In the liquid state, water can be gathered together, or concentrated, and even stored. Air remains in a gaseous, dynamic, or uncontrolled state and only in extremely rare places, such as through mountain passes is it ever naturally compressed enough to greatly multiply or concentrate its power. With wind power, man has to take it as it comes. With water stored in large lakes, man can control and use it as necessary.

By harnessing water, man is taking advantage of the effect of gravity on particles. If man can interrupt the water on its way back to a lower surface (sea level) and trap it in a natural valley by use of a dam, he has stopped the kinetic energy or movement of the water. It is held as potential or stored energy due to its higher position above sea level.

Calculating the Power Potential

The horsepower (hp) available in water is measured by the kinetic energy (KE) it possesses. If a cubic foot of water (12 inches on each edge) is allowed to fall a distance of 50 feet, it exerts a certain amount of force when it is suddenly slowed down or stopped. The formula for this, from AEES-22, Definitions, is:

$$\text{KE (ft-lb)} = \tfrac{1}{2}\,M \times V^2$$

A cubic foot of water weighs about 62 pounds, and the mass (M) has to be changed to weight divided by the gravity constant g, 32 ft/s^2. That is, w/g equals 62/32. The formula for the velocity (V) with which the cubic foot of water will be travelling when it reaches bottom after falling under the force of gravity for 50 feet is:

This can be substituted directly into the kinetic energy formula for V^2:

$$\text{KE} = \tfrac{1}{2} \times \frac{62}{32} \times 2 \times 32 \times 50 = 3{,}100 \text{ ft-lb}$$

If a cubic foot of water is released each second and allowed to fall 50 feet and strike a waterwheel, the horsepower possible is (see AEES-22, Definitions):

$$\text{hp} = \frac{\text{foot-pounds per second}}{550} = \frac{3{,}100}{550} = 5.64$$

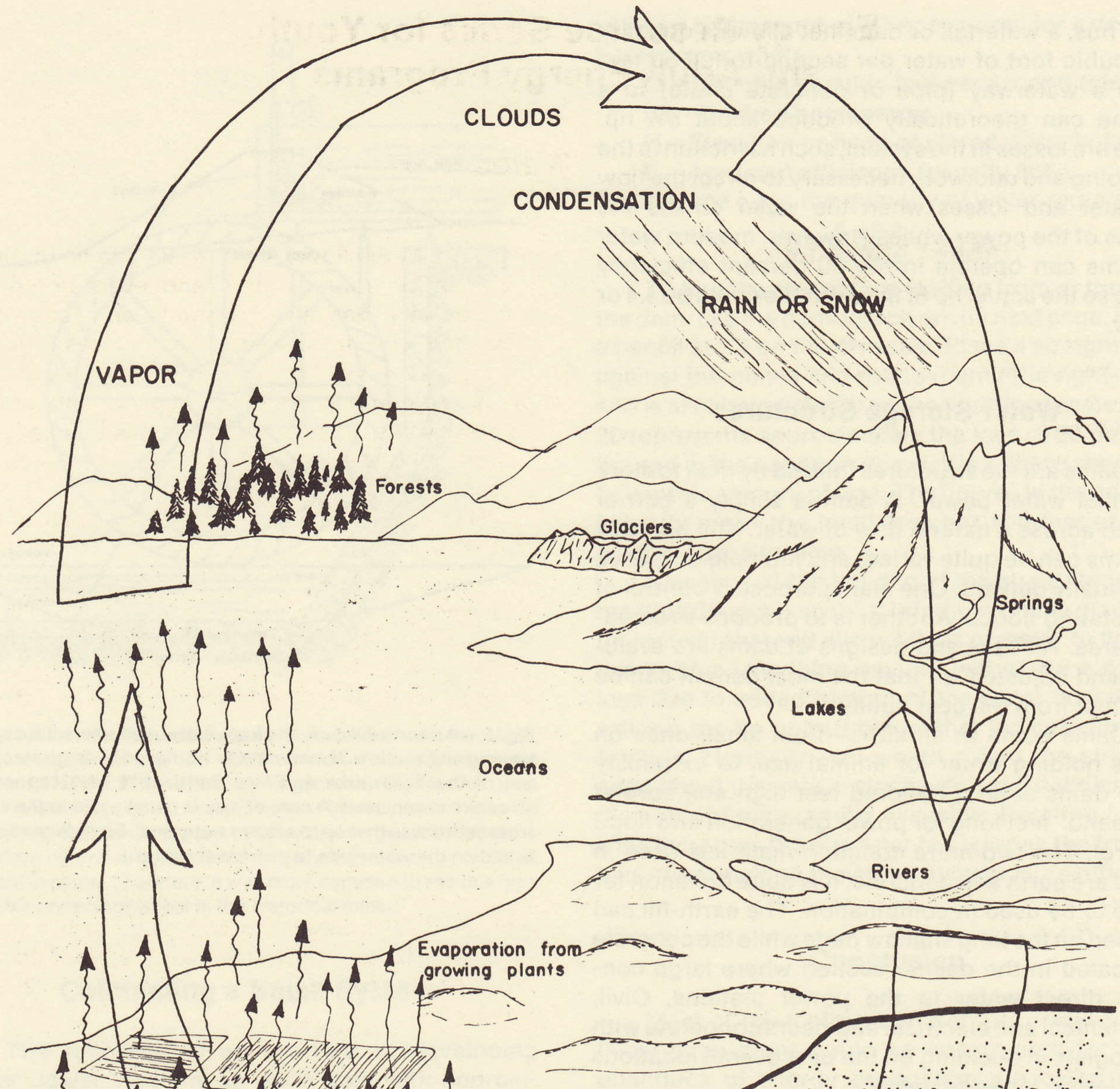


Fig. 1.—The natural water cycle which is technically called the hydrology cycle. It is on the highlands and edge of the mountainous regions that major water power sources exist.

Thus, a waterfall or dam that allows a quantity of 1 cubic foot of water per second to fall 50 feet down a waterway (pipe or concrete chute) to a turbine can theoretically produce about 5½ hp. There are losses in the system, such as friction in the plumbing and ductwork necessary to direct the flow of water and losses when the water strikes the blades of the power wheel. However, modern water systems can operate in the 80 percent efficiency range so the actual hp of the example could be 4.4 or better.

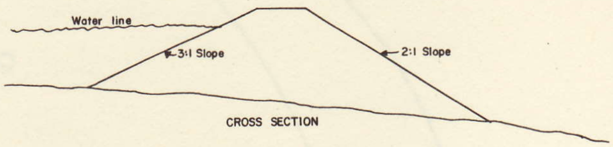
Water Storage Structures

Dams are the structures utilized by man to store potential water power. A dam is simply a barrier placed across a natural flow of water. The purpose of dams can be quite varied, and multiple purposes are usually derived. One main purpose is control of devastating floods. Another is to produce a recreation area. All uses and designs of dams are evaluated and adjusted, so that the most benefit can be obtained from the cost outlay.

Dams come in all sizes—from small ones on farms holding water for animal use, to extremely large dams several hundred feet high and several thousand feet long for power generation and flood control. The two more common materials used in dams are earth and concrete; it is quite common for these to be used in combination. The earth-fill can be used on the long shallow parts while the concrete is located in the deeper section where large conduits direct water to the power stations. Civil, mechanical and electrical engineers cooperate with geologists in deciding on the best overall locations and design for large dams.

Each dam is unique and is designed to fit the natural conditions of the location and the job the dam is expected to do. (See Figures 2, 3 and 4.) Where a proposed dam affects a large number of people, it must be discussed in public hearings and voted on by the public. It is important that the public be informed on the subjects discussed in this publication, along with information in other publications in this energy resource series. A well-informed person can make better decisions on questions concerning construction proposals of large-scale structures that affect the environment.

Dams constructed mainly for producing power are usually located so that the greatest depth of water can be impounded. The farther water falls before striking a turbine, the greater its velocity and kinetic energy; this allows the dam's turbine and



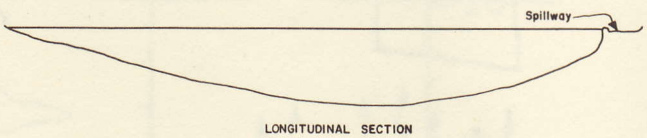


Fig. 2.—An earth-fill dam. It is frequently used where the dam will be long and shallow. If material can be moved by large machines out of the basin area and into the dam, a very economical structure is achieved. A core of clay is usually laid in the center from bedrock to the top to act as a water seal. Sometimes asphalt is laid on the water side to prevent seepage.

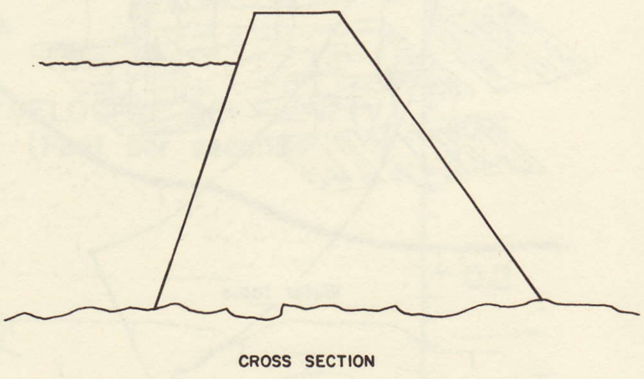


Fig. 3.—A gravity-type dam. This type of structure is just a massive hunk of concrete whose weight resists the overturning force of the water. This type of structure contains more material than a curved or arch type (Figure 4), but is quicker and easier to build.

the dams are used for locks to allow barge transportation, there is an advantage in not building the dams too high.

There is a common misconception that power generated by water is free, since it does not require any cash outlay for fuels as the fossil or nuclear fuel plants do. However, even though the operating costs of hydropower are low, the original cost of the dam and turbine generator is higher than for fossil fuel plants. This must be paid off.

An important fact about water power is that it is relatively pollution-free. This, in addition to such added benefits as decreased flood damage and creation of recreational areas increases water power's attractiveness.

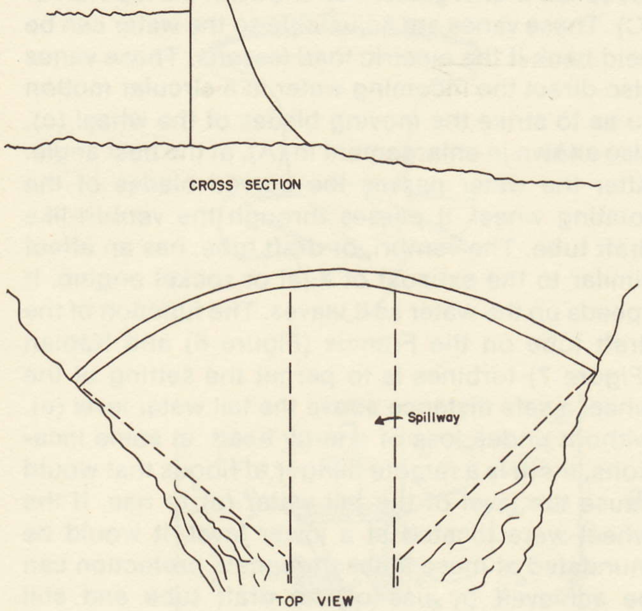


Fig. 4.—An arch dam. This type is used in narrow, rock-lined canyons of great depth. The arch faces into the water and resists its push just like an arch bridge can hold up a heavy load. These structures are of reinforced steel construction and can be rather hollow on the inside to save material and make construction a bit easier.

plumbing to be of smaller size. Engineers search for locations where this situation is possible, along with a reservoir and water shed of sufficient capacity to assure adequate water depth.

In general, if a sufficient quantity of water is present, dams providing low heads can provide as much total power output as dams of great height but with limited water. ("Head" refers to the height of water in a reservoir—the higher the water, the greater the pressure.) The surveyors and engineers consider all the facts to provide the best overall design for the location that nature provides.

The Tennessee River falls about 500 feet from its beginning to the Ohio River exit, a distance of 600 miles. The natural terrain along this route does not lend itself to the construction of one large dam for collecting water at a depth of 500 feet. A single dam would be too immense and flood too much land. The situation forced engineers to use several dams, lowering the river in steps. These dams together produce as much power as could one large dam. The head at each is less, but the quantity of flow is greater to create the same amount of power. Since

Water Turbines for Large Dams

Pelton Wheel

Usually engineers can take advantage of various heights or heads by using different types of turbine wheels. The Pelton wheel (Figure 5) is used for dams forming water depths over 500 feet. The turbine may be located at a great distance from the dam, and the water is conducted from the dam to the turbine in enclosed pipes called penstocks. In the

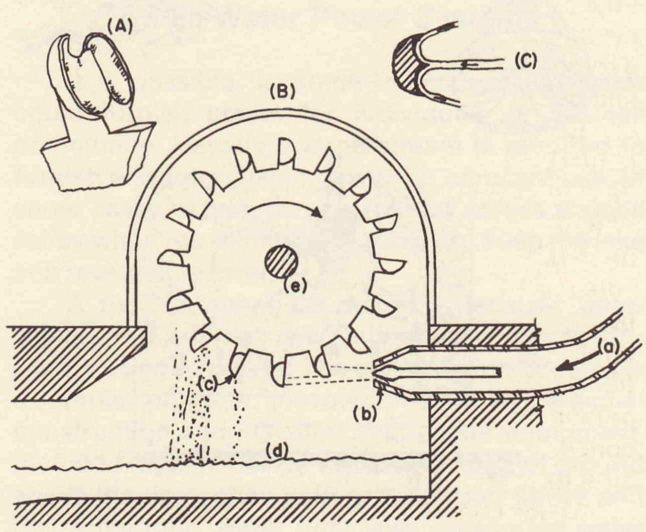


Fig. 5.—The Pelton wheel turbine.

cross section (B), the impounded water enters through the penstock (a). A nozzle (b) directs the water against the buckets (c) at the bottom of the wheel. The design is such that the force of the water is used up, and the water falls out of the buckets to the tail water (d). From there, it gently flows on downstream. The needle valve in the nozzle (b) adjusts the amount of water according to the electric load.

An enlarged view of one of the buckets is shown in (A). In (C), a top view of one of the buckets shows how the solid stream of water from the nozzle strikes the center of the bucket, divides, and reverses direction. This action eliminates end thrust on the wheel. After the water reverses direction back toward the nozzle, it has used all its kinetic energy and is moving so slowly that it simply falls directly below to the tail water. This type of wheel is very efficient, something above 85 percent. The major losses are the friction in the pipes and nozzle.

Francis-Type

The Francis-type water turbine (Figure 6) is used for intermediate heads of 100 to 500 feet. In the cross section (B), the impounded water enters the flume (a), which is usually formed right into the

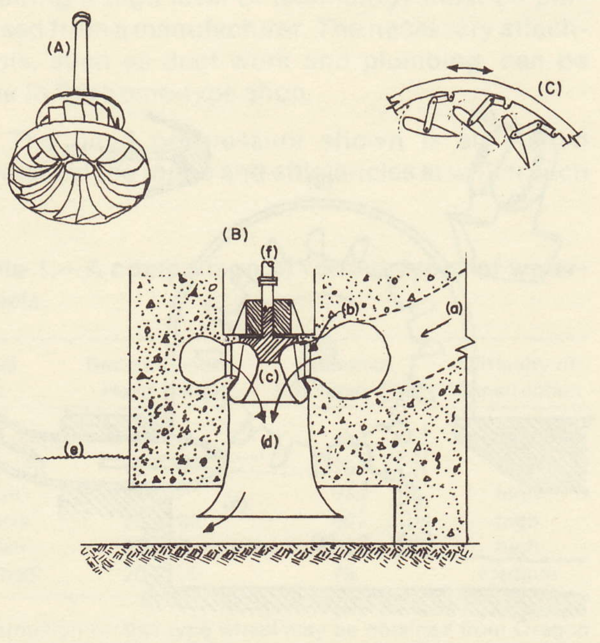


Fig. 6.—The Francis-type water turbine. This and the similar Kaplan turbine (Figure 7) are usually built right into the base of the back side of the dam.

dam, then passes into the spiral, snail-shell-shaped penstock that surrounds the turbine wheel. On the inner edge of the spiral penstock are vertical vanes (b) called wicket gates, also shown in the top view of (C). These vanes are adjustable so the water can be held back if the electric load lessens. These vanes also direct the incoming water in a circular motion so as to strike the moving blades of the wheel (c), also shown in enlargement in (A), at the best angle. After the water passes the curved blades of the rotating wheel, it passes through the venturi-like draft tube. The venturi, or draft tube, has an effect similar to the exhaust of a jet or rocket engine. It speeds up the water as it leaves. The function of the draft tube on the Francis (Figure 6) and Kaplan (Figure 7) turbines is to permit the setting of the wheel a safe distance above the tail water level (e), without undue loss of energy head. In some locations, there is a remote danger of floods that would cause the level of the tail water (e) to rise. If the wheel were located at a lower level, it would be inundated at these times. Adequate protection can be achieved by use of the draft tube and still maintain the effect of the full head of water. This is important in dam locations where there is minimum head to begin with. Draft tubes are usually not used on Pelton-type wheels (Figure 5) because the percentage gain is too small for the extra trouble and expense. The generator is located above the wheel and is connected directly to the shaft at (f).

Kaplan-Type

The Kaplan-type water turbine (Figure 7) is used for relatively low water heads in the range of 50 to 100 feet, but where there is a large quantity of flow. It is usually built right into the base of the back of the dam. As with the Francis-type (Figure 6), there is a solid flow of water through the turbine wheel and out to the tail water at (a). In the cross section (B), the impounded water enters through the flume (a) and then into the snail-shell-shaped penstock (b) which has guide vanes directing the water in a downward direction. The water then passes the blades shown in the enlarged view (A) which have the unique feature of being adjustable in the angle of attack against the water. This feature makes the Kaplan wheel very efficient at all loads. The housing fits snugly against the tips of the blades for efficiency. After passing through the blades, the water moves through the venturi-like draft tube with the same effect as with the Francis wheel (Figure 6) and exits at (d). The generator is directly connected to the turbine shaft at (f).

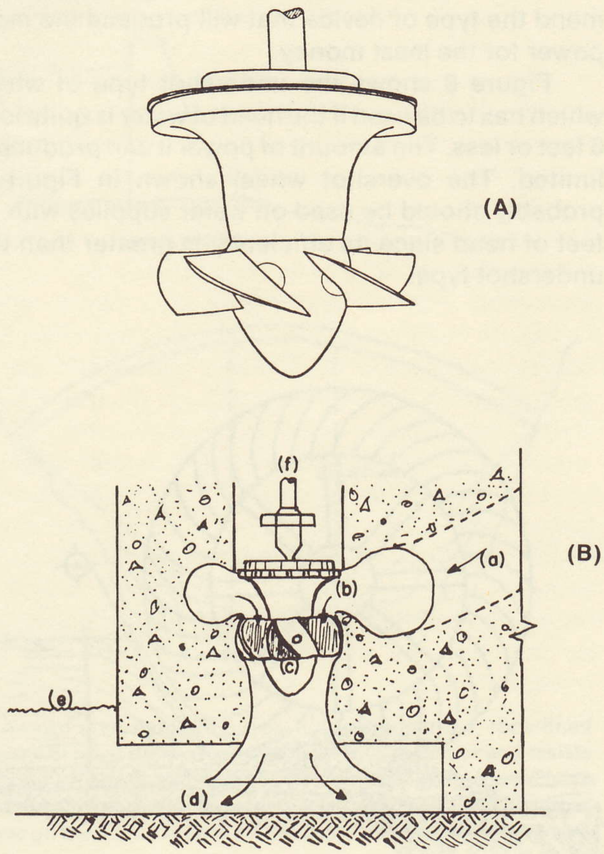


Fig. 7.—The Kaplan-type water turbine.

Other Water Power Potential

The potential power in the movement of the tides is mentioned frequently in the popular press and some periodicals. Engineers see this as a far less potential source than the use of large dams to store water with high static heads ready to produce power at the times and rates desired. These same engineers give wide application of tidal power the same regard they do wind power. Both are considered lower quality when compared to large dams. There are two reasons for this. First, the average head of water caused by the tides is quite low compared to that caused by the average dam, so the potential is just not there. Second, power is available only during the short time the daily tides run, and this may not correspond with the times when consumers want the power.

The places with the potential for generating tidal power are extremely limited compared to prospective dam sites. At some of these rare locations, engineers estimate that the cost of the elaborate system of low dams and dikes necessary to force the tides into a more favorable situation for harnessing would be as expensive as for one large dam elsewhere that has many times the power potential available at a constant rate anytime of day.

Because of these facts, the prospects for generating significant amounts of power from a tidal system seem remote. There are, however, a few locations in the United States where designs may be profitable, with more power returned over time than is required in materials and construction. At these places, even though the average head is only 20 feet and lasts about 6 to 8 hours per 24 hours, a water turbine similar to the Kaplan (Figure 7) is used. The difference is that the wheel is mounted on a horizontal axis rather than a vertical axis as in Figure 7, and the water is forced to pass through the blades by the close-fitting shroud formed in the dam. The wheel and generator are both completely submerged to the greatest depth possible for the greatest force (head) on the blades.

The Kaplan-type wheel is uniquely fitted to this situation because the blade angle can be changed. As the force of the water changes, the power output remains constant. When the tide water reverses itself and flows backwards, the blade angle of the Kaplan turbine is reversed so that power is generated as efficiently as when the water flowed forward. Usually several units are situated side by side in tidal dams to extract the maximum possible power from their location.

Small Water Power Systems

It is possible, in some instances, that water could furnish power for individuals or a small community. Usually a large stream is required to furnish enough reliable power for constant use. In some cases, a lake can be formed across a small valley when the rainfall is sufficient to keep the lake at a reasonable level.

A dam is generally required because water wheels and turbines need higher pressures to efficiently develop power. The construction of dams is a complex problem; it involves more than the actual construction and installation of power equipment. Included in an initial survey are flooding of ground above the dam; change in groundwater above and below the dam; water right laws; measuring water flow in running streams; estimating water flow from the water shed; and calculating the theoretical power available from a chosen site.

In general, a dam across a continuously running stream will furnish the same amount of water, at a higher head, that flowed in the natural stream. The dam across an intermittently flowing stream may furnish only moderate flow depending on the size of the reservoir and the watershed area to catch the seasonal rains.

In most cases, individuals or small community groups contemplating use of water power should employ a consulting engineer to do a feasibility study, develop plans, and make recommendations for the project. Good general references on the subject of building small dams are *Ponds for Water Supply and Recreation,* Agricultural Handbook #387, Soil Conservation Service, USDA; and *Building a Farm Pond,* Farmer Bulletin #2256, USDA. These can be obtained from the County Cooperative Extension Office, Soil Conservation Office or the United States Government Printing Office, Washington, D.C.

A small community should consider the types of wheels listed in Table 1. (If employed, a consulting engineer will make recommendations about the site, dam type and type of wheel to use.)

The listings in Table 1 are very general breakdowns of the types of rotating devices from which water power may be translated into electricity. The items showing low difficulty of construction may be put together in a well-equipped home shop. Those requiring a high level of technology must be purchased from a manufacturer. The necessary attachments, such as duct work and plumbing, can be done in the home-type shop.

The head or pressure shown is simply an estimate of the range and efficiencies at which each type might best operate. A qualified engineer can make a complete and accurate design and recommend the type of device that will produce the most power for the least money.

Figure 8 shows the undershot type of wheel which has to be used if the head of water is quite low, 6 feet or less. The amount of power it can produce is limited. The overshot wheel shown in Figure 9 probably should be used on water supplies with 10 feet of head since its efficiency is greater than the undershot type.

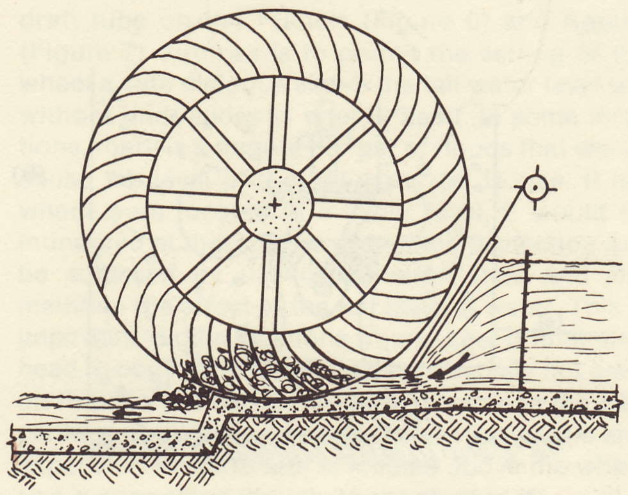


Fig. 8.—The undershot waterwheel. Water in a running stream backed up to a depth of 3 to 5 feet can make this type of wheel rotate. Not a great amount of power can be obtained, however, because the potential is just not there. Care must be exercised in forming the concrete bottom (the brest) so that a relatively tight fit results, while the large wheel does not rub it.

Table 1.—A comparison of various types of waterwheels.

Wheel Type	Recommended Head (Feet)	Estimated Efficiency (%)	Difficulty of Construction
Undershot	5 - 10	40	low
Overshot	10 - 40	75	low
Pelton	100+	85	high
Francis	50 - 100	80	high
Kaplan	25 - 75	80	high
Mitchell*	20 - 100	75	medium

*Information on this type wheel may be obtained from Oregon State University, Engineering Experiment Station, Corvallis, Oregon 97331.

The big disadvantage of waterwheels (Figure 8 and 9) is their slow rotation rate, 10 to 15 rpm (revolutions per minute). Because of this, there is great mechanical difficulty and loss of efficiency in "speeding up" to turn generators at an acceptable rate, 1,000 rpm or better. The waterwheel is best suited for jobs requiring slow movement. It does not offer much assistance in electrical generation.

Water turbines shown in Figures 5, 6 and 7, on a small scale designed for smaller water quantities, can be attached to generators since their rotation is faster—up to 20 times faster than waterwheels depending on the head available. These machines, however, must be purchased ready to install from a manufacturer.

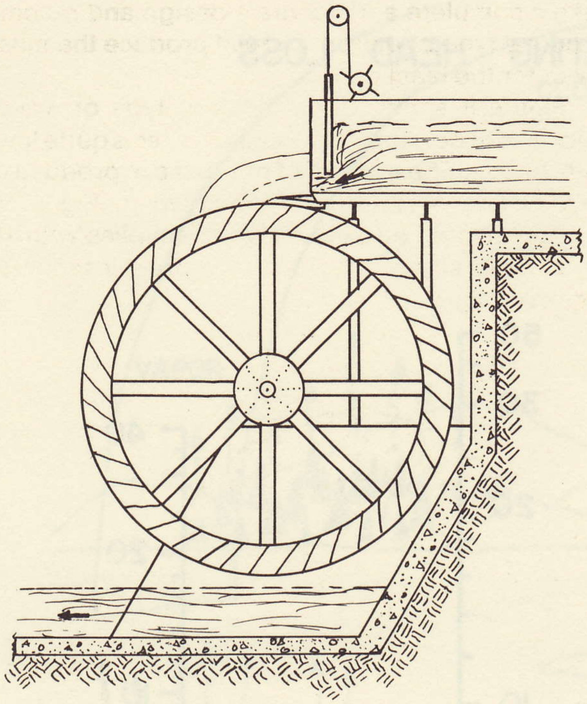


Fig. 9.—The overshot waterwheel. More torque and, therefore, more total power may be obtained from this type than the undershot wheel. The efficiency is generally higher. An open chute or sluicer (it could be a pipe) must be constructed to bring water from the dam to the top of the wheel. In general, if there is sufficient natural drop available, this wheel is easier to construct and put in place. Therefore, it was more common to see this type than the undershot wheel in the historical mills.

Calculating a Small System

The following is an example in developing water power. Assume an earth dam with approximately 25 feet elevation between the spillway and the draw below the dam in which a water turbine could be located.

The formula, $Q = \frac{hp \times 8.8}{H \times E}$ will give the amount of water required for a desired horsepower where:

Q = **Quantity in cubic feet per second (cfs)**
hp = **Desired horsepower**
H = **Elevation or head of stored water in feet**
E = **Assumed efficiency (usually 80%)**

To produce 5 hp, the quantity of water required is:

$$Q = \frac{5 \times 8.8}{25 \times .8} = 2.2 \text{ cfs}$$

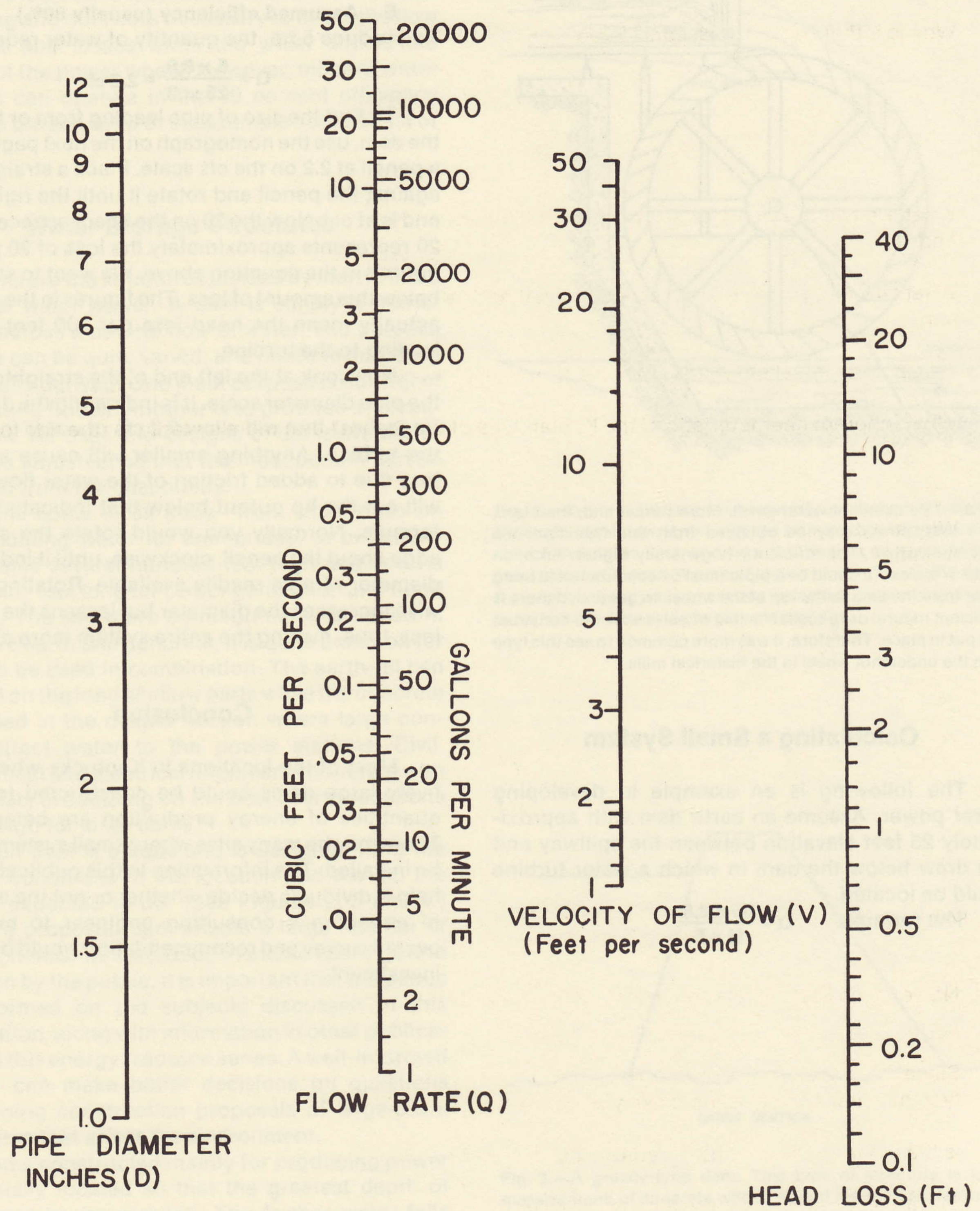
To find the size of pipe leading from or through the dam, use the nomograph on the next page. Place a pencil at 2.2 on the cfs scale. Place a straightedge against the pencil and rotate it until the right-hand end is at or below the 20 on the head loss scale. This 20 represents approximately the loss of 20 percent figured in the equation above. We want to stay at or below this amount of loss. The figures in the column actually mean the head loss per 100 feet of pipe leading to the turbine.

Now look at the left end of the straightedge, at the pipe diameter scale. It is indicating the diameter (in inches) that will allow 2.2 cfs of water to flow to the turbine. Anything smaller will cause a higher loss due to added friction of the water flow which will cut the hp output below that indicated by the formula. Normally you would rotate the straightedge about the pencil, clockwise, until it indicates a diameter of pipe readily available. Rotating clockwise increases the diameter but lessens the friction loss, thus, making the entire system more efficient.

Conclusion

Most of the locations in Kentucky where relatively large dams could be constructed for large quantities of energy production are being used. There may be many sites where small systems could be installed. The information in this publication can help individuals decide whether or not the expense of engaging a consulting engineer to make an overall survey and recommendation would be a wise investment.

NOMOGRAPH FOR ESTIMATING HEAD LOSS



Questions

To stimulate thought and greater understanding of water as an energy source, answer the following questions with the correct word(s). Refer to the text when necessary.

1. Why is it that each dam is considered an individual by its designer? ____________________

____

2. Why is water considered to be of higher quality than wind for power production? ____________________

3. What are two of water power's most important advantages? ____________________ and ____________________

4. What two things cause engineers to think that tidal water power will always be limited? ____________________ and ____________________

5. Which type of turbine wheel fits the tidal situation the best? ____________________

6. What inherent characteristic of the Kaplan type of turbine makes it more suitable for the tide location?

____

7. Why are dams needed to furnish small amounts of power by waterwheel for individual homes or communities? ____________________

8. What is the ultimate source of water power? ____________________

9. Because of its ultimate source, water power is close kin to what other source of energy? ____________________

10. Water stored above a dam is considered as potential energy. When some of this water is freed and falls upon a waterwheel, it is what type of energy? ____________________

11. How much does a cubic foot of water weigh? ____________________

12. The natural water cycle is technically called what? ____________________

13. What are the three general categories or types of dam construction? ____________________ ____________________ and ____________________

14. Name some of the dams that may be beneficial for other than power production. ____________________

15. Since most of the dams on the Tennessee River system supply a head of water at 100 feet or less, what type of water turbine is most likely to be used? ____________________

16. Is the power generated by a hydroplant free? (Yes or No) ________

17. Explain your answer to question number 16. ____________________

____

18. Could water power furnish our power requirements if every available location were developed, regardless of economic consequences? (Yes or No) ________

19. If a family or a small community thinks they have a potential place for developing water power, what are some things to consider? ____

20. What is the big disadvantage of the waterwheel for use in turning a generator? ________________

21. Why is a qualified engineer recommended as a designer for the small hydropower system? ________

Answers

1. The natural conditions where it is located vary, along with its use.
2. It is many times more concentrated.
3. renewable and relatively pollution free
4. intermittency and low head
5. Kaplan
6. The blades can change angle with water speed and direction.
7. Waterwheels and turbines need the higher pressure for efficiency.
8. sun
9. wind
10. kinetic
11. 62 pounds
12. hydrology cycle
13. earth-fill, gravity, arch
14. recreation, prevent flooding
15. Kaplan
16. no
17. The cost of construction must be repaid.
18. yes
19. flooding of ground by impounded water; change in water flow below the dam; water right law; calculating power available
20. its slow rotation speed
21. Water power systems of any size are quite complex and trained, experienced persons should do the planning.

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